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Scaling up concentrating solar thermal technology in China

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ABSTRACT

More than 1300 GW new generating capacity will be added in China's power sector over the period 2005–2030 under the BAU scenario in [1], even higher than the total installed capacity in the United States to date. China's industrial and service sectors are expected to maintain rapid development rate over the next decades, driving up the demand for electric power and heat. However, China's power and industrial process heat generation are heavily relying upon coal-fired thermal power plants resulting in tremendous rise in greenhouse gas emissions. Clean technology such as concentrating solar thermal (CST) needs to play a more important role in power and heat generation in China to accelerate the decarbonisation in the power sector and commercial and industrial process heat generation cost-effectively. This paper attempts to explore the opportunity and challenge of development and deployment of CST in China from both technical and socioeconomic analysis perspectives. It is argued that rapid deployment of CST in China will contribute to enabling sustainable energy supply and environmental securities, as well as improved economic performance in new technology innovation in Asia Pacific area over the next decades. Supportive policy framework should be set up to encourage scaling up CST industry. The success of deployment of CST technology will also allow Chinese power and heat generators to strengthen their competitiveness in the context of intensified global constraint of carbon emissions. Institutional innovation and policy instruments for scaling up this technology and the enabling conditions of successful implementation are also investigated.

Contents

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1. Introduction

Recent analyses on climate sensitivity suggest that a responsible risk management strategy would be to keep emissions levels within the lower end of the probability range associated with a 2 °C increase; this means that reducing greenhouse gas (GHG) emissions is a critical imperative for international community. More than one-third of global CO_2 emission is related to fossil fuel combustion in the power plants [2], energy efficiency and renewable energy sources provide the most promising means of dramatic reductions in greenhouse gas emissions. As one of the fastest-growing economies in the world, China's future energy demand trend and supply technology have significant implications in shaping global climate regime over the next decades. IEA estimated that China's primary energy demand and CO_2 emissions in 2030 would be nearly 2.5 times as much that of 2004 under the business as usual scenario, more specifically, coal will still represent more than 60% of total energy supply at that horizon [1]. As the major contributor to energy-related CO_2 emissions, China's power sector will play an essential role in emission mitigation to fortify global energy and climate securities over the next few decades. The BAU scenario risks locking China's energy sector in high emissions trajectory over several decades, this irreversible process will pose a formidable challenge to energy and environmental securities as well as sustainable economic growth to China's policy makers. Therefore, decarbonising China's power generation and industrial processes with carbon-free technologies is an imperative for the next decades.

China's fast economic growth risks being restrained by scarcity of energy resources, per capita recoverable oil and gas reserves in China represent only 11 and 4.5% of the world average, respectively [3]. At present more than 50% of China's oil consumption relies on imports and it is likely to exceed 80% in 2030 [1], most of which come from the Middle East States where the risk of geopolitical uncertainty may thwart China's long-term energy supply security. Energy efficiency and local renewable energy can contribute to lowering the risk of energy supply interruption and minimising the environmental impacts. High oil price scenarios may provoke strong price volatility in the international energy market; subsequently hindering the economic growth if China's energy sector cannot move gradually towards efficient and low-carbon generation technology in the coming years.

Solar energy development is underpinned by a favourable global market and domestic energy policies in China. China topped the list with a commitment of US$6 billion in investment in renewable energy development worldwide (a total of US$38 billion) in 2005.[1] However, compared with China's total capacity of 508 million kW for all forms of energy, the overall shares of renewables (24.3% for hydropower, 0.5% for wind, and even smaller amounts for others) remain limited. According to the Chinese Medium and Long-Term Development Plan for Renewable Energy [4], renewable energy is expected to account for 16% of China's total energy supply by 2020, up from 7% in 2005, implying enormous room for development [5]. It is widely accepted that the successful development and deployment of large-scale renewable power generation such as solar energy in both developed and developing countries can make substantial contribution to safer energy supply and global climate change mitigation. Concentrating solar power and thermal technology provides promising options to sustainable energy supply. Ordinary solar-heating technology is suitable for supplying medium and low-temperature hot water (40–70 °C), primarily used for residential water and space heating. But this range of temperature can hardly meet specific energy demand such as industrial process heat requirement and electric power generation. In this regard, the concentrating solar thermal (CST) technology appears to be a promising technology since the system converts the highly concentrated solar energy into high-temperature steam which then allows generating electricity with virtually no GHG emissions. In addition, cogeneration and or tri-generation systems based on CST can also be designed to reduce further the production cost compared to Photovoltaic electricity. The scope of this paper is focused on CST technology and its likelihood of large-scale deployment in China's power generation, industrial process heat and space heating in buildings.

In a recent review paper [6] published in this journal, the technical aspect and prospect for development of concentrating solar power (CSP) technology in China have been addressed. However, despite its obvious social and environmental benefits, CST technology is still heavily limited to small-scale demonstration projects, dwarfed largely by conventional fossil fuels-fired heat and power generators with cheap fuels which are heavily subsidised by government.Solar concentrating technology will only account for less than 1% of total electricity generated in 2020 in most projections in recent literature on the long-term energy demand scenarios in China. The widespread uptake of this environmentally friendly technology is being hindered by both technical complexity and investment uncertainty, mainly due to lack of policy support and appropriate market incentives.

2. CST: a promising technology to address climate change

Indeed, various technical options can allow achieving GHG emissions reduction imperative: fuel switching(from coal to natural gas in power plants), energy efficiency, renewable electricity production and so on. CST and CSP with optical concentration technologies are important candidates for providing a major share of the clean and renewable energy needed in the future to address the challenge of long-term energy and climate securities [7]. The energy that the earth receives from the sun each hour is equivalent to current yearly primary energy supply of the world [8]. However, we often overlook the fact that the solar is actually the most abundant energy sources on the earth, and policy markers in energy sectors have considered solar energy only as a marginal contributor to the long-term cleaner energy and climate security strategies. This is mainly due to the twofold inherent drawbacks of solar energy. First, despite a high quality energy source because of the high-temperature and exergy at its source, the power density at the earth's surface makes it difficult to extract work and achieve reasonable temperature in common working fluids [7]. Second, the intermittence of solar irradiation means that the source is available only in daytime, thus heavily weather dependent, but the resource is weaker when heating demand is greater in winter in the northern countries and regions [8]. These technical barriers can be addressed effectively by concentrating solar thermal technologies. Incident sunrays are tracked by large mirrored collector matrix (heliostats), which concentrate the energy flux towards radiative/convective heat exchangers, called solar receivers, where energy is transferred to a working thermal fluid (e.g. oil or water). After energy collections by solar subsystem, optical concentrators, and solar receiver, the conversion of thermal energy to electricity has many similarities with the fossil-fuelled thermal power plants [7]. Concentrating solar power's relatively low cost and ability to deliver power during periods of peak demand-when and where we need it-mean that it can be a major contributor to the nation's future needs for distributed sources of energy [9]. The first commercialized 11 MWe CSP power plant installed in Spain has been designed to produce 23 GWh of electricity a year—enough to supply a population of 10,000. CSP has undergone rapid development over the past 20 years, in particular in the United States (California, Nevada), Europe (mainly Spain and

[1] Spending on large hydropower projects is excluded.

Fig. 1. Parabolic concentrating solar collector field at Kramer Junction, California (superior left) and direct steam generating parabolic trough of the DISS project at Plataforma Solar de Almeria, Spain (superior right) [11].

Germany) and several parts of Japan with a number of successful cases. In 2005, the world's solar power generation capacity amounted to 120 GW and 600 TWh electricity was generated [10].Based on optimistic projection, CSP is likely to account for about 7% of global generating capacity by 2050 in the mitigation scenario [10].

2.1. Technical characteristics

Now, there are three different CST technology options, namely parabolic trough, tower and dish Stirling, respectively. The solar thermal concentrating devices are included in these systems: direct normal insolation (DNI) is reflected and concentrated onto a receiver/absorber where it is converted to heat, and then the heat is used to produce steam to drive a traditional Rankine power cycle. Below we describe briefly their function principles and the major characteristics.

2.1.1. Parabolic trough

Parabolic trough system is the most proven and widely deployed CSP technology. This is primarily due to nine large commercial-scale solar power plants, the first of which has been operating in the California Mojave Desert since 1984 (SolarPACES website [12]). Large fields of parabolic trough collectors supply the thermal energy used to produce steam for a Rankine steam turbine/generator cycle. Successful experiences in the US and Spain show that a well-designed solar trough system (nine SEGS projects) can be in profitable commercial operation [13].The solar field is modular in nature and is composed of many parallel rows of solar collectors aligned on a north-south horizontal axis. Each solar collector has a linear parabolic-shaped reflector that focuses the sun's direct beam radiation on a linear receiver located at the focus of the parabola. The collectors track the sun from east to west during the day to ensure that the sun is continuously focused on the linear receiver [11,14](Fig. 1).

2.1.2. Power tower

Power tower system is characterised by the centrally located large tower (Fig. 2). A field of two-axis tracking mirrors (heliostats that individually track the sun and focus the sunlight on the top of a tower) reflects the solar radiation onto a receiver that is mounted on the top of the tower, where the solar energy is absorbed by a working fluid, then used to generate steam to power a conventional turbine. To maintain constant steam parameters at fluctuant solar irradiation or even at the time of no shining, the system can be integrated with a fossil back-up burner or a thermal storage unit [6,15].

Central Receiver Systems have a large potential for mid-term cost reduction of electricity produced since they allow many intermediate steps between the integration in a conventional Rankine cycle up to the higher exergy cycles using gas turbines at temperatures above 1300 °C, and this subsequently leads to higher efficiencies and larger throughputs. By concentrating the sunlight 600–1000 times, they achieve temperatures from 800 °C to well above 1000 °C.

2.1.3. Solar dish

Solar dish systems consist of a dish-shaped concentrator (like a satellite dish, see Fig. 3) that reflects solar radiation onto a receiver mounted at the focal point. They consist of clusters of small mirrors

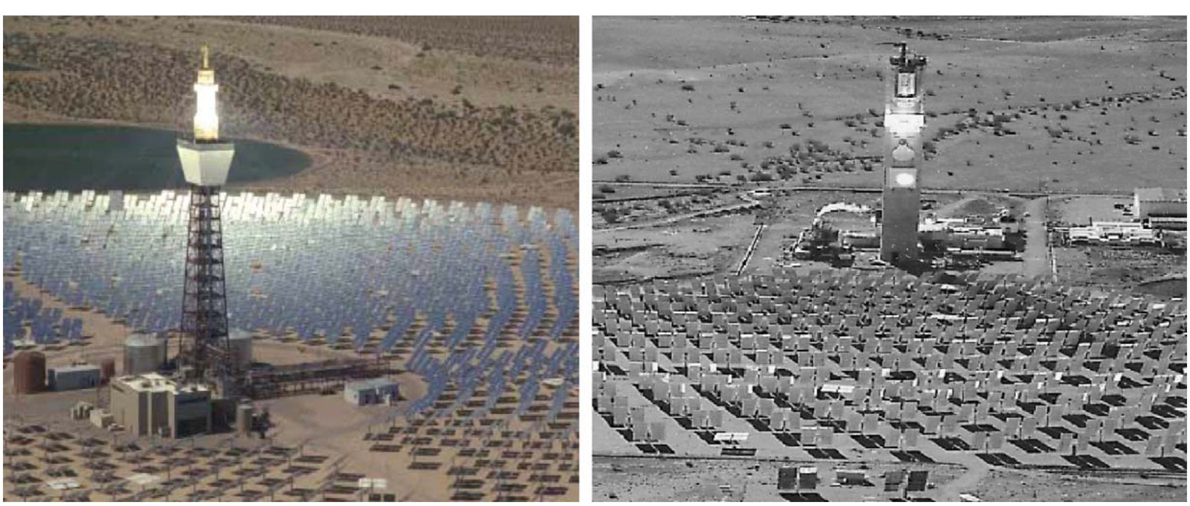

Fig. 2. Solar II central receiver plant in Barstow, California (superior left) and CESA-1 of 1.2 MW in Almeria, Spain (right).

Fig. 3. The EURO-DISH parabolic dish concentrator with a Stirling motor generator (Plataforma Solar de Almeria, Spain).

set into modular, circular arrays to pinpoint solar energy onto a receiver situated above each dish. The receiver may be a Stirling engine and generator (dish/engine systems) or it may be a type of PV panel that has been designed to withstand high temperatures. The Stirling engine uses heat to vary the pressure inside a hydrogen-filled sealed chamber. This drives pistons to produce mechanical power. Several dish/engine prototypes have successfully operated over the last 10 years, ranging from 10 kW (Schlaich, Bergermann and Partner design), 25 kW (SAIC) to the 400 m^2, 100 kW "big dish" of the Australian National University. Like all concentrating systems, they can additionally be powered by fossil fuel or biomass, providing firm capacity at any time. Because of their size, they are particularly well suited for decentralised power supply and remote, stand-alone power systems [11].

3. Why should CST deployment be scaled up in China?

3.1. Solar energy: an emerging industry in China

Currently, solar energy industry in China has an annual turnover of more than 100 billion yuan (15 billion US$ in 2005). The total installed capacity of solar thermal in China reached 39,000 MW, most of which use evacuated tube technique. However, the most common solar water heater found in the market, even with the use of vacuum tube technology, can only deliver at most 70 or 80 °C hot water in summer, and 40–50 °C in winter. This temperature range is suitable for residential space and water heating and sanitary usage (shower). However, it can hardly meet the requirements of high-temperature heat steam for industry process and power generation. Therefore solar water heater alone cannot provide a fundamental solution to China's energy supply bottleneck, the use of concentrating system by effectively improving solar energy density to produce high-temperature heat steam turns out to be an effective energy supply alternative to conserve the depletable fossil resources and address growing concerns about environmental hazards associated with fossil fuel combustion in power and heat generation.

As far as solar PV industry is concerned, China has become one of world leaders of solar PV manufacturing with a production capacity of 820 MW in 2007, only second to Japan. Solar cell manufacturers in China now have an annual production capacity of 1300 MW and plan to expand this to 4000 MW by 2010—more than the entire global production in 2007 [16]. Nevertheless, the CST technology for power generation and industrial process heat lags largely behind the development of PV and Flat-Plate solar panel.

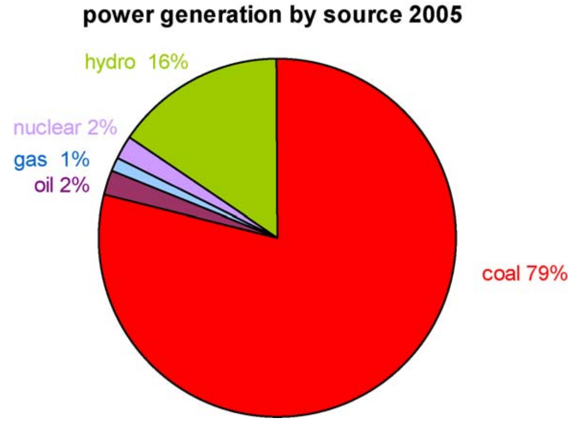

Fig. 4. power generation in China by fuel.

3.2. Power sector

High dependence on coal in the power sector (see Fig. 4) could bring about the question of energy supply security and more importantly, will have considerable carbon emissions implications. The mono-supply portfolio of coal-fired large power sector could result in technology lock-in with detriment to innovative power generation technologies in the next decades. Moreover, deployment of CST for distributed electricity will contribute to increasing electricity distribution efficiency and reducing grid loss as well as minimising the power outage risk in case of technical failure of centralised power grid.

Driven by strong economic growth, power generation in China has been increasing dramatically since 1990, total electricity generated increased nearly four times, growing from 621 TWh in 1990 to 2475 TWh in 2005 [17]. The rapid growth trend in power sector is expected to continue in the next decades. China's power sector needs an investment of more than 1.8 trillion US dollars over the period 2001–2030 [1]. Decision on energy infrastructure investment has tremendous implications in terms of long-term GHG emissions, especially for a country like China with predominating coal use in the primary energy supply mix. In 2005, the national average unitary coal consumption of power generation was about 353 g/kWh, which is still about 23% higher than the most advanced international level. Coal-fired thermal power plants are responsible for more than one-third of China's total energy-related CO_2 emissions.

The Chinese government is committed to shutting down more than 40 GW small-sized (unit less than 50 MWe) inefficient thermal power generation capacity by 2010 in accordance with national scheme of energy efficiency improvement [4].In addition to improving radically the energy efficiency in the thermal power plants, the solar power generation is proven to be one of promising alternative technologies to enable China to move towards low-carbon power generation. Table 1 summarises the BAU scenario of Chinese power sector development up to 2030. Coal-fired generating capacity will triple over the period 2000–2030. It can

Table 1
Projected power generating capacities in China

	Coal	Oil	Gas	Hydro	Nuclear	Wind	Biomass	Total
2000	215	9	3	76	2	1	1	306
2005	368	13	5	121	8	1	1	516
2010	612	16	23	179	11	16	2	859
2020	650	23	93	348	61	42	12	1229
2030	662	22	138	410	134	124	33	1523

Source: BAU scenario of [18].

be seen that China would have to add as much as 700 GW additional generating capacities by 2020, roughly equivalent to the EU's total existing capacity in 2004. More than 1300 GW new generating capacity will be added in China over the period 2005–2030 under the BAU, even higher than the total installed capacity in the United States to date [1]. In the scenario of [18], large-scale carbon capture and storage (CCS) technology will need to be deployed in most of large-sized power plants since the likelihood of climate constraints will be much higher in the post-Kyoto regime. However, the CCS technology is still confined to the pilot scale and the most optimistic estimate is that it will only be commercially viable in the coal-fired power plants beyond 2015–2020 or even later, depending on technological advancement rate and specific global climate policies. Prohibitive cost, technical unmature,uncertainty about leakage and regulatory issues also impede the likelihood of large-scale deployment of CCS in the coal-fired power plants in China in near term. Therefore, CCS alone can hardly address the long-term climate constraints without supply technology diversification in China's energy sector as no silver bullet exists to ensure energy and climate securities alone.

Each week, China adds one additional 1 GW coal-fired generating capacity to keep in pace with the effervescent economic development. The generation technology chosen today will shape the carbon emissions trajectory for several decades since a power or thermal plant will last for at least 30–40 years before retirement. The irreversible nature must be taken into account in investment decision making on energy infrastructure installation otherwise it would result in the long-term carbon lock-in. It would be a great mistake if China will pursue an energy development trajectory without seizing the huge potentials for solar energy of which CST is a promising option and offers a sustainable energy development perspective for China.

In its 11th 5-year plan, the Chinese government defined ambitious objective aiming at reducing 20% GDP's energy intensity by 2010. In addition to improving drastically energy efficiency, Chinese energy policy markers have also committed to diversifying energy supply since China's economic growth train is heavily replying upon coal which represents nearly 70% of the country's primary energy supply in 2005 if biomass in rural area is excluded [19]. Wind, hydro and nuclear generating capacity are expected to reach 30, 300 and 40 GW by 2020, respectively [3]. Although solar energy is available throughout the country, development pace of large-scale solar power and heat generation still lags behind the conventional energy sources.

Noticeably, it is projected that renewable energy will only account for a tiny part in the increased generation capacity. This is quite consistent with the estimation of [1], which projected that electricity demand in China will more than triple during the period 2005–2030, increasing from 2544 TWh to 8472 TWh per year under BAU scenario. However, only 15 TWh electricity will be produced in solar power plants in 2030, almost negligible compared to coal-fired power generation (6586 TWh). It will only account for 1% of total generated electric power even under the policy scenario under which more supportive policies on energy efficiency and renewable energies are expected to be implemented. This scenario still places too small weight on scaled development of concentrating solar power in China.

As mentioned earlier, power sector is a major contributor to the GHG emissions in China, the life-cycle greenhouse gas emissions factor is about 1.3 kg CO_2eq/kWh$_e$ in coal-fired power supply chain [20]. Although hydro and nuclear power generation have very low CO_2 emission factors compared to coal and other conventional hydrocarbon fuels, environmental and ecological impacts and ethical issues relating to these projects have raised enormous public concerns about land use change and nuclear waste disposal. Switching massively from coal to gas in the power sector is unlikely to occur. On the one hand, gas is much more expensive than coal, the latter is the most abundant energy sources throughout the country, and the price ratio of gas to coal is approximately four in China, compared with only two in the US and most of European countries. On the other hand, fuel-switching policy has potential threat to China's long-term security of energy supply since a significant part of natural gas will be supplied by Russia and Eurasian Countries. Recent disputes and tension between Russia and Ukraine (and also the European Union) reveals considerable geopolitical risk and supply fragility of high dependence on imported natural gas. Natural gas supply intermittence occurs already regularly in China, in 2006, 6000 MW of natural gas-fuelled power generation units were forced to shut the production of electricity due to serious supply shortfall. Gas supply and demand will hardly equilibrate over the next 20 years in China, the Chinese Academy of Engineering projected that domestic natural gas demand will increase at 10.8% per year over the period 2000–2020, whereas supply will grow only 7.5% per year [21].

Another modelling study projected that China's electricity generation-related GHG emission in 2020 would more than triple as much that in 1990 to reach 1554 Mt CO_2eq under the BAU scenario of [22]. Switching partly from coal to renewable, as assumed in the Policy scenario will allow for 23% reduction relative to BAU. However, CSP development will only allow 1% of reduction or 155 Mt/year in 2020 in their projection. Note that CSP penetration in their projection is relatively conservative (only plants smaller than 200 MW will be replaced). In fact, most of new installed coal-fired units in China are 600 MWe or even larger. CSP can contribute to significant cut in CO_2 emissions if deployed more rapidly in the large-sized units. Moreover, these scenarios do not take into account the scaled application of CST in building sector. As explained above, CST can be used to a greater extent for district heating and hot water supply in densely populated urban residential districts to substitute partly the distributed coal-fired boilers.

3.3. Industrial process heat and buildings space heating

Both industrial and service sectors have been growing very fast and thus offer an unprecedented opportunity of technological innovation and promoting the whole supply chain of solar energy. Industry represents more than half of final energy consumption in China and is the major driver of electricity and heat generation capacity addition [1,17], largely higher than in OECD countries (22%).Overall, industry and buildings together consumed 2270 TWh electricity and heat in 2005, accounting for nearly 50% of CO_2 emissions in China [1]. Industrial demand for energy is expected to increase 3.2% per year over the period 2005–2030, growing from 478 to 1047 Mtoe. Note that more than half of final demand in industry sector is thermal requirement. This implies that CST development is far more interesting in industrial cities where civil and industrial heat demand can be integrated into the same centralised distribution system. Fig. 5 shows that industry and buildings will be the major drivers of increase in final energy demand in the next decades (unit : Mtoe).

Industrial process heat is widely used in food&drink, textile and chemical industries covering a variety of industry process: drying, washing, pasteurising, cooking, sterilising, heat treatment, bleaching, dyeing, distilling, chemical process, feedwater pre-treatment, space heating, etc. [10]. The required temperatures range between 30 and 200 °C depending upon specific process. The industrial process heat consumption in China is about 90 Mtoe/year, accounting for nearly 20% of total final consumption in industrial sector [1,17], equivalent to the total district heating consumption in the buildings sector.

In the meantime, building sector's share in final energy demand has been growing steadily and is expected to pursue the strong

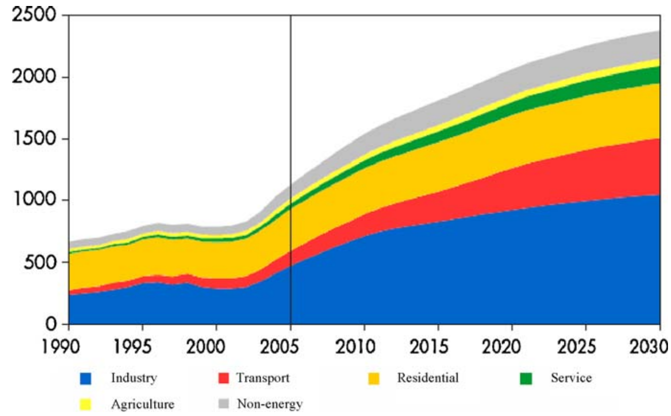

Fig. 5. Projected final energy demand in China by sector [1].

growth trend in the next decades [23]. The rising urban dwellers will need more energy services such as space heating and cooling, as a result of improved standards of living of urban inhabitants. CST can also be used as an effective alternative for district heating in northern cities and centralised air conditioning in transition area based on absorption cooling technique. Consequently, CST will also play a critical role in cutting greenhouse gases emissions related to fossil fuels combustion for meeting energy demand in buildings. District heating in China's urban area represents already almost 40% of total energy demand in buildings. Nearly 93 mtoe of coal [25] was burned for district heating per year, this does not include electricity consumption for heat-pump air conditioner in winter in the transition climate zone. The centralised heating floor area increased from 1100 million square meters in 2000 to 2500 million m^2 in 2005 [26], most of which is supplied by coal-fired district boilers and thermal power plants. Each year, the CO_2 emissions associated with urban district heating in Northern China is equivalent to the total emissions in Poland [27]. Thus the rapid growth in industrial and buildings sectors in the next decades offers an unprecedented opportunity for CST technology deployment with appropriate policy and strong signals combined with market-based economic incentives. CST and CSP technologies would have huge potentials in power and heat market penetration provided that appropriate energy policies will be put in place.

4. The way to large-scale deployment of CST and CSP in China

Although huge potentials for large-scale deployment of the CST technology remain unexploited in China, market penetration of the system in commercial and industrial sectors is still very low. The next few decades will be critical for the development of CST and CSP technology due to the fact that power generation and final energy efficiency improvement constitute together the backbone of global GHG mitigation over the next decades [28].

4.1. Harnessing available technologies to achieve effective solar energy scaling-up

Chinese solar industry has already acquired relatively matured technical know-how and the industry supply chain of solar manufacturing industry has emerged. Currently, the solar thermal energy is primarily used in places where households have no access to centralised electric power grids. As of 2003, the installed capacity of PV is about 50,000 KW, mainly installed for residential electricity supply, traffic light and communication devices in remote inland areas [29]. Some industrial processes also use sunlight power for sea water desalination and other industrial and agricultural activities such as drying and farmland irrigation and hydrogen production. Some high-tech solar technology has also been developing fast in China, for example, a carbon nanotube technology has achieved a major breakthrough in the thin-film PV by creating photoelectric cell with conversion efficiency nearly 12.6% [30].

Solar energy is primarily used for Chinese domestic water-heating in residential sector. Flat-Plate and evacuated glazing solar heat-collecting module are the most common technologies for hot water production. Scaled R&D investment is needed to improve further the thermal efficiency in the technology prevalence of solar thermal products. For example, the state-of-the-art technique of electrochromic vacuum glazing with selected low-emittance coatings can allow improving the thermal performance significantly [31].

Building-integrated solar technology offers a broad perspective for future solar technology markets. China is now the biggest solar heater supply in the world. The vast construction boom across the country implies huge potentials for solar energy technology applications. More than 2 billion square meters of floor area of buildings are constructed each year in China since 2000 which is higher than any other countries in the world. The Chinese Ministry of Construction has estimated that around 15–20 billion $m^2$of urban-zone housing will be built between 2005 and 2020 to accommodate newcomers to the cities [24], implying an enormous potential of demand for solar-integrated homes, including building integrated PV, solar-fuelled space and water heating. If 50% of the all the new buildings in the country will be equipped with high-efficiency solar heating collector to ensure space and water heating, nearly 73 million tonne equivalent of oil (mtoe) fossil energy could be saved, subsequently, 260 Mt of CO_2 emissions would be avoided in 2020 [23].

Western provinces (West Qinghai, Southeast Xinjiang, North-west Gansu, North Ningxia and West Tibet) are the most promising areas for large-scale development of CSP and CST technologies, where the average altitude is more than 4000 m, yearly direct solar insolation is greater than 2200 kWh/m^2. In addition, due to the low-density of population in these regions, the development of centralised power distribution is economically inefficient, the need of deployment of off-grid power such as distributed supply of CSP and CST in the small villages is imminent. Fig. 6 illustrates the solar insolation distribution in three western provinces in China.

4.2. Prospect for scaled deployment of CST

There has been an exponential growth in PV production in China since 2003, increasing from 1% to 18% of the global PV production market within only 4 years [16]. With more than 400 solar PV companies, China's growing solar manufacturing industry will bring keen competition in the international solar energy market. Solar PV industry is advancing at breathtaking rate: more than 30% per year! [33]. There are already four Chinese solar companies with market capitalisations of over US $2 billion: SunTech Power Holdings, LDK Solar, JA Solar Holdings and Yingli Solar. However, it should be noted that China's solar growth has largely been fuelled by growing international demand from countries like Germany, Spain and the USA, rather than by domestic demand, and solar technology still provides less than 0.2% of total electricity needs within China. The challenge of meeting domestic renewable energy targets could trigger sturdy growth for China's solar manufacturing leaders in the future renewable energy markets [16]. The main tendency could also be duplicated in the development of large-scale CST projects.

As mentioned earlier, huge potentials of energy conservation and carbon emission abatement remain untapped in China's power and heat generation sector. CST technology can be applied in both industrial and buildings sectors to supply industrial process heat

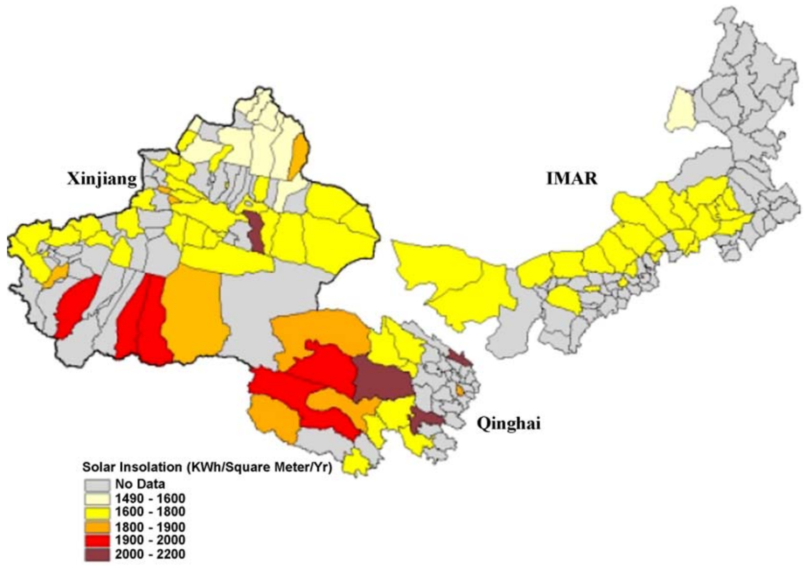

Fig. 6. Solar resource distribution in three western provinces [32].

and electricity. This technology will play an essential role in both mitigating carbon emissions and supplying high quality electricity and heat to final consumers. However, due to lack of market incentives and institutional barriers, the development scope of concentrating solar technology is still limited to a few number of small-sized pilot projects, large-scale deployment will need appropriate supportive mechanisms such as fiscal and economic incentive and electric power purchase contracting (e.g. feed-in tariff). It is widely recognised that supportive policies should be put in place to facilitate low-carbon technology uptake in initial stage. Both the market drag and policy push forces are necessary in underpinning scaled development of this promising technology. Market failures can be corrected by well-designed policy portfolios, including capital subsidy, feed-in tariffs of green power, certificates/obligations, and fiscal mechanisms such as tax credit and reduction. These support mechanisms are fundamental to the industry's growth and are essential for scaling up the industry. Some meaningful lessons can be learnt from renewable power capacity scaling-up in Germany which has a successful experience of development of renewables through the Erneuerbaren-Energien-Gesetz (EEG) (Renewable Energy Act). In 2006, the share of renewable energies in total electricity consumption was 12%; about 45 million tonnes of CO_2 were saved thanks to implementation of the EEG. The share of renewable energies in total electricity consumption should increase to at least 20% according to the government's projection, and would have risen to 45% by 2030 [34]. Fig. 7 shows the rapid development of electricity generation from renewable sources in Germany.

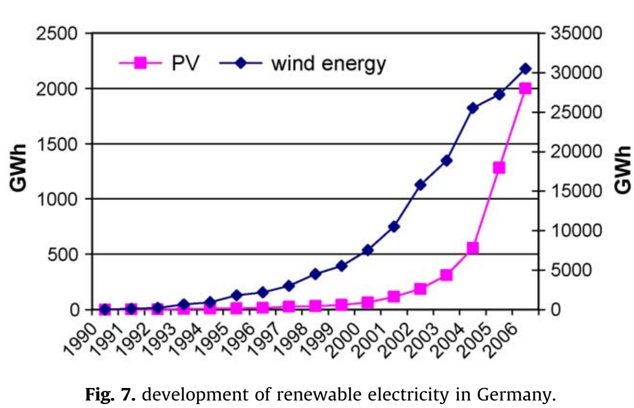

Fig. 7. development of renewable electricity in Germany.

The promotion of photovoltaic (PV) electricity generation is a major aspect of the integration of renewables in buildings. The German government has put in place several regulatory frameworks and schemes to stimulate the development of building-integrated PV system by guaranteeing a long-term price. The installation of solar-panel systems benefited from a low-interest loan until 2000 in the programme of 100,000 roofs. In 2004, the programme was replaced by Renewable Energy Law (REL), which sets a fixed payment rate for solar electricity [35]. Similar incentives and policies can be established in the power and heat generation sector in order to facilitate channelling investment into CST market. Large-scale development of CST will also create a large number of new job opportunities in the whole industry chain through vertical and horizontal integration (material manufacturing, equipment installation builders, maintenance and operation engineers and skilled workers, transporters). This will not only reinforce the local competitiveness of new technology development but also strengthen the energy supply security, and more importantly, providing a cost-effective means of long-term GHG emissions abatement.

4.3. Creating the enabling environments for innovation and diffusion of CST technologies

Power, industrial and buildings sectors are expected to maintain high-rate development over the next decades. CST is one of proven and sustainable power and heat supply options. However, CST technology deployment strategy needs to embrace the innovation in the whole supply chain, rather than focusing on particular areas such as research and development of a specific technique. Several reinforcing elements are needed [36]:

- consistent policy signals to move investment towards CST,
- growth of the capital pool available for investment in research and commercial-scale demonstration projects,
- clear market-pull instruments to drive commercialization, e.g. through CST portfolio mandates, tax credits, investment "matching funds", public procurement policies and funds from CO_2 compliance payments; implementation of a supportive institutional framework,
- promotion of training of solar technology engineers and technicians,

- energy efficiency and CO_2 compliance in upstream industrials, and
- promote the free flow of expertise, know-how, novel ideas and experience in CST sector.

4.4. Overcoming financial bottleneck

Financing constitutes one of the major challenges to the deployment of CST technologies in the buildings and industry sectors where there exist significant barriers to capital formation. Economic theory suggests that new technology is often perceived as expensive by investors due to information asymmetry or cost of acquisition of adequate information. Regulatory uncertainty, proof of technical feasibility and lack of a critical mass of intellectual capital and market demand for power and heat generated from CST plants all conspire to keep the scale of investment flows to this low-carbon technology very small, relative to the level required [37].In addition, most investors in China's power and heat production sectors are unfamiliar with CST technology and therefore perceive it as risky, which increases the cost of capital.

A range of custom-designed instruments will be required to finance the deployment of low-carbon technologies such as CST. In fact, CST is ready for large-scale and rapid deployment but requires well-designed financing mechanism from different players in the market. Public resources will prove insufficient to meet the financing requirements of CST technology. This must derive from private initiatives. There ought to be cooperation between public and private financial players to boost the start-up of large-scale CST, capital cost is expected to decrease over time thanks to learning experience and economies of scale.

Removing the inherent barriers to widespread diffusion and scaled deployment of CST necessitates innovative policy tools and reform of the existing institutional framework. Financial institutions such as commercial banks should get involved more actively in the financing of high-efficiency energy supply system development programme. Carbon financing mechanism can be introduced to promote CST market. The Clean Development Mechanism (CDM) of the Kyoto Protocol offers an mutually beneficial financing alternative in fostering CST projects. International financial institutions (private carbon trust in particular) have been extensively involved in the implementation of CDM projects in China's power sector. China's first CDM project was a 25 MW wind power plant in collaboration with Dutch buyer of CERs. The potential of CO_2 emission reduction in China's power sector of CDM project is expected at 73 Mt CO_2 per year [38]. However, most of CDM in China is focused on HFC gas mitigation whose GWP may be as much as 12,000 times that of CO_2, HFC-23 accounts for more than 70% of CERs in all CDM projects in China up to 2007, whereas power sector only represents 10% of total (see Fig. 8). Note that there are virtually no CERs transacted by implementing solar project. CDM in China needs further design reform in order to realise the great potentials for deploying green technologies of power and heat generation and mitigating CO_2 emissions. The Chinese policy-makers should move faster to seize the opportunity offered by this win-win bilateral and or multi-lateral financing cooperation mechanism.

Furthermore, the white certificate scheme implemented in several European countries could serve as a model for increasing CST's market share. A nationwide CO_2 allocation scheme for the power generators and district heating operators could be instituted by the central government and supervised and implemented by the relevant local regulatory bodies. The most efficient, low-carbon generators of electricity and heat could be granted extra certificates or emission allowance, tradable as "credits" on the financial market within sectoral players. In addition to financing instruments innovation, a sectoral carbon tax could also be levied to bridge the investment gap in light of large-scale deployment of CST.

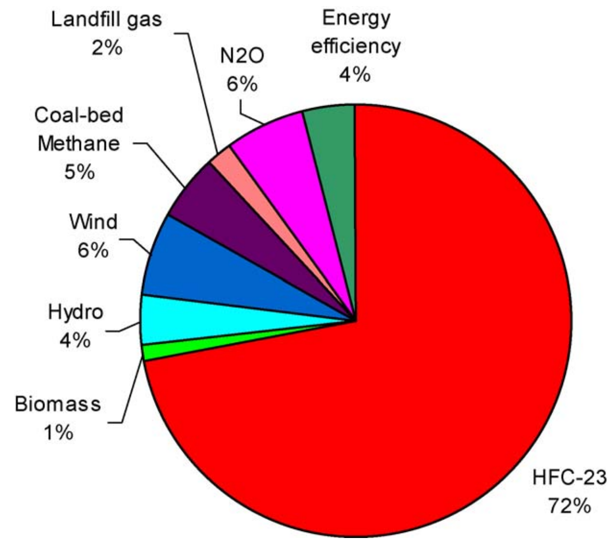

Fig. 8. CO_2 reduction of CDM in China in 2007 [1].

Both regulatory and market-based tools are required to boost CST market, technological forcing, feed-in tariff of CST supply and carbon tax can be implemented conjointly to incentivise power and heat industrials to move gradually to low-carbon generation technology. This requires further commitment of national power regulators and strong government intervention.

Different actors play specific roles in CST industry development, Utilities, CST and CSP IPPs, CSP/CST developers, Components manufacturers, EPC providers. The combinatory mechanism should be aimed to give appropriate incentives to each of them such that they can cooperate with each other more actively and effectively. Both vertical and horizontal integration of CST and CSP industry are necessary to bring about outreach of this technology.

4.5. Inclusion of externalities, learning experience and portfolio risk

Although capital cost of carbon-free power and heat generation technologies like CST is still higher than the conventional coal-fired power plants, but the perspective of increasing cost of primary fossil energy ought to be taken into account. In addition, it is necessary to internalise the cost of externalities of CO_2 emission since climate change constraint must be addressed. The capital cost of coal-fired power plants will increase substantially with additional decarbonisation installation such as CCS which raises concerns about energy penalty and regulatory uncertainty on underground storage source. The post-Kyoto international climate regime is expected to tighten given the urgency of tackling the irreversible global warming. China has already overtaken the US as the biggest CO_2 emitter in the world in 2007 [39], future scenario of development in China's energy sector is of crucial importance for achieving global climate protection goal. Levying carbon tax or raising carbon price in China's industry and power sectors is likely to help channel capital (both human and material resources) towards carbon-free power and heat generation technologies.

Moreover, the economies of scale and learning experience (learning-by-doing) will together allow for further decline in capital cost of large-scale CST investment. Previous studies show that the global solar PV module cost has declined by a factor of nearly 100 since 1950s [40], and over the period 1972–1992, each doubling of sales of PVs reduced the price by 18% [41]. From economist viewpoint, if the probability is an increasing function of prevalence of use of a new technology, then the use of that

technology can be expected to spread like a disease [42]. All these theoretical and empirical studies hold that there being tremendous potential for further decrease in installation cost of CST and make it more competitive and attractive.

Furthermore, raising the share of CST in China's power and heat sectors will decrease the energy supply portfolio risk. As suggested in [43],this can be illustrated by a simplified financial risk assessment model by considering two energy supply technologies 1 and 2, the weighted portfolio risk is estimated as the covariance of two technologies, expressed in Eq. (1)

$$\text{Expected portfolio risk} = E(\sigma_p) = \sqrt{\lambda_1^2\sigma_1^2 + \lambda_2^2\sigma_2^2 + 2\lambda_1\lambda_2\beta_{12}\sigma_1\sigma_2} \qquad (1)$$

where λ_1 and λ_2 are the fractional share of two technologies in the portfolio; σ_1 and σ_2 are the standard deviation of the returns of annual costs of technologies 1 and 2, respectively; β_{12} is coefficient of correlation.

Both theories and empirical studies in energy economics show that the fossil energy prices are inherently correlated with each other(oil, gas, coal, etc.) to certain degree, thus a mono-fossil energy supply portfolio is exposed to future uncertainty risk, in other words, it is more sensitive to fuel price volatility in international and domestic energy markets. Conversely, inclusion of renewable energies (e.g. concentrating solar) will diversify the supply portfolio and reduce the expected risk because their costs are not correlated with fossil fuel prices (β_{12} is virtually nul). Thus, developing CST in China's power sector and industry heat process generation will allow reducing significantly the vulnerability to fuel price fluctuations and ensuring supply security given China's heavy dependence on coal and imported oil.

4.6. Institutional reform

Power and district heating pricing reform should be implemented more quickly in China's buildings and industry sectors. Final energy consumption is still heavily subsidized by the government, in particular the electricity and heat prices. The electricity price is reviewed by the regulatory authorities through administrative approach and may not necessarily reflect the real cost of production, let alone the externality costs associated with environmental impact. The marginal pricing approach has hardly been employed by the power regulator in China. In many circumstances, some industries benefit from specific power allocation based upon agreement with local government. CST-generated electricity and heat could not be competitive if the final energy prices are set artificially low. In most of northern cities in China, heat consumption in residential buildings is billed proportionally to occupied floor area of the dwellings instead of actual use. Consumers do not receive any unbiased price signals of heat consumed, this non cost-reflective pricing system results in huge energy loss and inefficient energy supply system management. No private investors will take the risk in developing the CST in district heating unless clear market price and transparent regulations and relevant institutions are properly established. In short, the existing regulatory institutions of power and heat generation require fundamental change to pave the way for large-scale development of CST in the coming years.

5. Conclusion

This paper investigated the development prospect and major challenges of concentrating solar thermal technology in China over the next decades. It is argued that CST technology will play an essential role in reducing carbon emissions in China's power generation and heat supply for both buildings and industry sectors where huge potential for GHG mitigation remain untapped. However, scaling up CST requires appropriate policies and institutions otherwise this technology cannot be cost-effective and will be hardly competitive with the conventional power and heat generation technologies.Institutional reform in the energy sector will be necessary to ensure the sucess of CST technology scaling-up.

Consistent policies to channel investment towards CST and clear market-pull instruments need to be implemented to drive scaled deployment of CST in China. Policy portfolio comprising mandates, tax credits, investment "matching funds", programmatic CDM, public procurement and funds from CO_2 compliance payments can help facilitate the uptake and increase probability of widespread deployment of this promising technology. After all, cost of externalities must be internalised (based on the model of carbon tax) in cost-benefit analysis to render CST more competitive. Also, policy makers should move quickly to accelerate the energy pricing reform to remove the financing barriers to the investment in CST development.

There exist both challenge and opportunity for China's social and economic development in the next two decades which will be a key period for global GHG emissions mitigation, to which China's successful transition to low-carbon economy can make substantial contribution. In this regard, CST technology must receive greater attention to make an outreach in decarbonising heat and power generation cost-effectively in China, this will make substantial contribution to grappling with global warming.

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